Introduction to Electric Power Systems

by Patrick H. Stakem

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Introduction

This book covers the topic of the electrical power used around the world, an focusing on generation, storage, transmission, and usage.

Our industrial civilization is dependent on a steady flow of electricity. But demand does not often equal supply for various reasons.

Author

The author has a BS in Electrical Engineering from Carnegie-Mellon University, and Masters Degrees in Applied Physics and Computer Science from the Johns Hopkins University. During a career as a NASA support contractor from 1971 to 2013, he worked at all of the NASA Centers. He served as a mentor for the NASA/GSFC Summer Robotics Engineering Boot Camp at GSFC for 2 years. He teaches Embedded Systems for the Johns Hopkins University, Engineering for Professionals Program, and has done several summer Cubesat Programs at the undergraduate and graduate level.

The first electrical systems used the direct current format of Nikola Tesla. There were problems with distance, due to excessive loss in the copper wire. It would work in a factory, but not in a city block. Direct current is also a form of flowing energy that can be captured in a battery.

A superior system was used by Thomas Edison, the alternating current scheme. Here, the source, called the alternator, was simpler than its dc generator counterpart. He used a frequency of 60 Hertz. In the alternator, the voltage is limited by the strength of the insulation on the wires. You want to make the voltage as high as possible for transmission, to reduce losses. The advantage of alternating current is that you can use a transformer to do this, and another transformer at the load end to bring the voltage back

down. You've seen these cylindrical transformers up on power poles.

Edison's first power plant used six dynamos and could produce 100 kilowatts, which could service a square mile of New York real estate. Edison also invented the electric meter, so he could bill his customers based on usage.

Standards

There are a variety of standards for electrical power. We have to agree on frequency (50 or 60 Hz) voltage (8 standards world wide), current, and mechanical standards - the shape of the plug and arrangement of the prongs. There are different mechanical configurations used world wide for plugs and sockets. . Cars generally provide 12 volts dc to the “cigarette lighter” plus, and most now come with USB charging ports.

The generation of Electricity

Electricity is used when it is generated. We run into the scenario that we need power at night for lighting, but our solar arrays are not generating. We have to be clever, and store energy when it is available, for use when it is needed.

No storage/source will be 100% efficient, so we loose some of our daytime power as we draw it out at night.

In the simplest case, during the day, we use solar generated power, and charge a battery with what we don't need. At night, we operate from the battery, using an inverter to get back to AC. We size the system so the heaviest load at night will operated properly in the hours of darkness, and that the solar panels have enough power to charge the battery's on a cloudy day. Battery's do lose capacity as they age, and have a finite number of charge-discharge cycles. They also have a maximum service life.

Wind turbines generate AC power, usually 60 Hz and 600 volts. A transformer is used to supply the appropriate voltage to the grid.

The turbines have a minimum “cut-in” speed, where they can start providing useful power This is around 10 MPH.

Similarly, there is a certain minimum amount of brightness for a solar panel to supply useful energy.

Today, the electrical grid is alternating current (AC). That was not always case. The very early market and technology was direct current, the favorite of inventor Thomas Edison. He was the expert, and defined the industry and the components. He got the first successful light bulb lit up in 1879. Now he could sell these to businesses and households, and then sell them the electricity to make them work. In 1880, he formed a company, the Edison Illuminating Company. His first electric utility was the Pearl Street Station in New York City. He supplied 110 volts of direct current to some 59 customers in Manhattan. In 1882, he opened a steam-power generating station in London.

If you didn't like DC, invent your own and capitalize it. As a proponent of alternating current and one-time Edison employee, Nikoli Tesla did just that.

Tesla was a Serbian American who contributed greatly to the development and deployment of AC power. He became a naturalized citizen of the U. S. in 1884. He worked for Edison in New York City briefly. He later worked on wireless transmission of power, and communications.

Other early inventors such as George Westinghouse were also convinced that AC was the way of the future. In what has been called the Current Wars, both sides pointed out how dangerous and inefficient the other side's system was. Tesla's design for an poly-phase AC motor was licensed by Westinghouse. Edison's DC system only served customers within 1 mile of the generating plant. Despite the drawbacks, Edison's marketing brought lighting, refrigerators, washing machines and such to small community's across America (including the Author's home town, Cumberland, Maryland).

In what came to be called the War of the Currents, the established

DC systems faced off with the upstart AC systems. Transformers were built by Westinghouse, to boost the voltage for transmission, and lower it at the customer's premises for safe use. Thinner wires were needed (although better insulation) for AC. In 1887, Westinghouse had 68 AC stations, to Edison's 121 DC stations. By 1892, the war of the currents came to an end. Edison was bought out, and a new company, General Electric, was formed.

But, alternating current was ultimately the right answer, and dc disappeared except for some trolley systems. Locomotives used dc until switching systems that could handle the high currents involved. All modern locomotives use AC power, and some are hybrid systems with a battery and inverter.

Why did ac win? Early systems were dc, because it was easier. The problem was, there is no way to distribute it widely. You might have a coal fired system for a small town, but each town needed one. It's also hard to switch large currents. They tend to melt the switch. For AC, you switch when the current goes to zero, momentarily. Out of high school, my father worked for Westinghouse, in the design of 'mercury arc" rectifiers. These could quench the big arc when switching large currents. They were used in the conversion of ac to dc. Generally, all real loads have resistance, capacitance, and inductance. If the current is in phase with the voltage, you have real (can do work) power. Since the load has capacitance and inductance, the current will be out of phase with the voltage. This produces what is called reactive power, which does no work. It just flows between the source and the load.

An AC system generates alternating current. If this is fed to a strictly resistive load (like a space heater) , the generated power is transformed into heat. If the load is not purely resistance, it will have the property's of capacitance and inductance.

Synthetic Inertia in power systems means delivering power when the system frequency deviates from its nominal value, due to a disturbance. In a large rotating system, energy is stored in large rotating machines. Wind, battery, and solar systems do not fit in

this definition. It is sometimes referred to as grid inertia.

Storage of Electricity

Mostly, we do not actually store electricity, but we are increasing the potential energy of air or water, or a big box of rocks, by using excess electricity at the time. We can turn this potential energy back into electricity easily, but the process is not 100% efficient. If electricity is not used when generated, it has to be stored. If a generation system is prone to the quirks of nature (as is solar and wind), then energy has to be stored when it is available, and released when it is needed. Large manufacturing plants might adjust their production schedules to take advantage of lower cost power.

Our power system, or grid, consists of sources of power, a distribution network, and users of power. The grid is the network of electrical networks. It includes the generation and distribution equipment. If there is no storage, then electricity is used as it is generated, and the system must respond to varying loads. By 1836, the telegraph system used battery's. There were storage battery's used to level the demand and supply. Pumped storage hydro was used by Connecticut Light & Power in 1929, a 31 megawatt pumped storage system. Power was also stored in flywheels. Today, pumped hydro represents the majority of power storage around the globe.

The grid is managed across the country. In the U. S., there are three grids, East, West, and Texas. Texas is a historically independent state.

Tesla's alternating current systems proved much better at transmission, and replaced the Edison DC systems after a while. Some dc systems survived for trains and trolleys.

Direct current can be stored in battery's, but AC has to be stored in potential energy systems such as pumping water back uphill to the

hydro dam. There is no free lunch. Each method of generation and storage is slightly inefficient, and some power is lost. We can convert ac to dc or vice versa with a motor-generator set, where, for example, a DC motor would drive an AC alternator. AC can be turned into DC by the rectification process. In the early trolley era, the motors were dc, and commercial AC power was used, rectified at the trolley facility. Most trolley systems today use a new generation of efficient AC motors. Locomotives, for example, use onboard diesel engines to turn alternators which supply motors at each axle. A feature called “dynamic braking” is used, when going downhill, to control speed. Essentially, the motors are driven in reverse, and generate power which is dissipated in large banks of resistor grids on the roof. This won't stop a train completely, but it does reduce brake wear. Make a note of this, we will run into it again later.

Not before the mid 1980's did the power company's use energy storage. At that time, there were coal-fired and some nuclear plants, and expensive gas-fired peak power plants. Coal was the cheapest option, so excess power was generated and stored in a variety of methods. The coal plants did not need to be designed for the peak demand, but only the average. Pumped hydro was the preferred solution for storage.

Storage can also be implemented at the customer site, where costs are controlled by purchasing and storing power when it is cheapest.

Solar systems evolved into large generators of power, as the cost of production of the cells decreased. Large “solar farms” sprung up, some with tracking arrays that followed the sun to maximize power. Wind farms also sprung up as the economics evolved, and became another non-fossil fuel, non-nuclear option. Unfortunately, solar arrays only work when the sun is shining, and wind turbines, only when the wind is blowing. Clearly, a storage system for energy is needed.

The electricity that is used for a myriad of purposes is generated as it is needed. There is not much “slack” in the generating infrastructure. Nuclear plants can adjust the output by varying the control rods in the reactor, which control the heating of water for the generators. Similarly, gas-fired plants can throttle back on the amount of gas entering the burner. Most coal-fired plants do not use raw coal, but powered coal that is blown into the combustion chamber. The control is called “load following.”

Storage system can respond to varying loads much better than the generating systems.

Another issue is the sudden loss of a electrical generator or a transmission line. Today's interconnected electrical grid is fairly agile at making changes, but you might see the lights blink. Storage can smooth this out.

Sometimes, an energy storage facility at a customer's site can prevent the need for new transmission infrastructure. The customer can download a constant level of power, part of which is stored, so the generation system can operate more smoothly.

Capacitors store energy in a electric field. An inductor stores energy in a magnetic field, as long as current flows through it. Capacitors all “leak” to a certain extent, and lose their charge over time. UltraCapacitors are very high capacity. There is a thin line between an ultra-capacitor, and a battery.

With the interest in electric cars, much more efficient batterys have evolved, that carry more power per weight, and are fast charging. Tesla, the current front runner in the field, uses Lithium-ion batterys. In the cars, the batterys weighs 900 pounds and has some 6,800 individual cells. It includes a liquid cooling system to prevent overheating of the battery pack.

The battery has about a 5-year working life, with replacement units costing $3 to $7 thousand dollars.

Tesla also markets the PowerWall, which is a big battery bank in your garage or basement, charged by solar arrays. The 2.0 version costs $6700, including installation, but not the solar arrays.

The Transmission of Electricity

The electric transmission and distribution system is called the grid, due to its architecture. They are individual switches and safety mechanisms, used to minimize damage in the case of lightning strikes or downed wires. You've seen the big tall towers carrying the transmission wires. The top-most wires are grounded, making them the target for lightning. The transmission is two-phase, using 2 wires with a neutral, 3 wires required. The frequency is 50 or 60 Hertz, depending where you're at. Actually, there are eight standards in use across the globe. There are a number of standards for the plug type and size.

The voltage is 10's of thousands of volts. Raising the voltage minimizes the line loss, which is due to the resistance of the wires. Transformers at the generating plant raise the voltage for transmission, and at a substation, which might serve a community, other transformers reduce the voltage for local distribution.

For example, I live in the United States, so my frequency is 60 Hertz, handy for running electric clocks. The wires that enter my house are two-phase, rated for 100 amps. There are three wires, a neutral, and two power wires. These come into an electrical box, where there is a bank of circuit breakers. Generally, large consumers of electricity such as air conditioning, stove, dryer, get their own circuit breakers. Other breakers may be for a room's outlets and lights.

A really good idea is to have a “whole house” surge suppressor installed at the box. If lighting hits the lines, that unit protects all the house wiring. Otherwise, your TV and computer would :^).

The grid is managed across the country. In the U. S., there are three grids, East, West, and Texas. Texas is a historically independent state.

From a central control, the grid is monitored and controlled, and can be reconfigured if some portion of it has failed.

Rarely do you have or even want a generating plant next to your home or businesses. Particularly nuclear (accidents do happen) or coal burning. This means we need an infrastructure of transmission equipment. The big problem is, the voltage needs to be a high level (100,000's of volts), to keep the transmission losses low. Power is voltage times current. With high voltage, we have a correspondingly lower current. Resistive losses in the wires is related to resistance squared. As much as the early dc power systems enabled things like lighting not involving gas, washers and dryers, and refrigerators, you had to be within a few miles of the generating plant. You can use a gas-refrigerator, my Aunt had one, but it still needed to be plugged into the wall outlet, to run the compressor.

Electrical power transmission is inefficient for low-voltage, high current systems., For DC, you can't easily transform the power into higher or lower voltage, it has to be generated at those points. In physics, Joule's first law says the heat generated by an electrical conductor is proportional to the product of the resistance times the current squared. Thus, we want to keep the current low, and to achieve the same power, we make the voltage high. This is difficult to do with direct current.

With AC, we can readily take what we generate, boost the voltage, lower the current, and reduce the voltage back to a standard (110 volts for the US) for safe usage in user devices. The first transformer was in use in 1881.

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Cars typically has a 12 volt dc system, but the U.S. Military prefers 24 volts. Electric cars have their own battery system for the drive motor, and an auxiliary 12 volt system, so you can recharge your phone.

Electrical Power in Space

Satellites have batterys and solar cells to keep them charged. A power regulating unit called the peak power regulator is in charge of the charging. The voltages and currents are telemeter-ed to the Earth-based control center for evaluation and logging. Satellite voltage can be whatever the equipment is designed for, and have an efficiency of around 14%. The solar cells are controlled by a Peak Power Tracker that optimizes the battery charging. The battery's State of charge (SOC) is continuously monitored.

On the international Space Station there are large solar arrays. These track the sun, to optimize energy collection. There are currently 8 of these arrays used to generate electricity. Each has 33,000 cells, and is 35 x 12 meters in size. In direct sunlight, the arrays generate 240 kilowatts of power, The arrays were designed for a 15 year service life. Currently, NASA is launching

replacements.

The Station's original Nickle-Hydrogen battery's have been replaced by Lithium-ion. There are 4 battery assembly's, each with a capacity of 110 ampere-hours.

For long missions away from the Sun, a radioisotope Thermal generator is sometimes used. The radioactive fuel provides heat, which is captured to generate electrical power. Their working life is decades. One problem is the security and handling of the radioactive fuel. Another problem is, that during the launch phase, if the rocket explodes, the radioactive material could be scattered over populated areas.

Mars receives enough sunlight to use it for charging batterys, but the arrays have to be much larger. Beyond Mars, its hard to get usable sunlight. One interesting concept is using a large solar sail, which is covered in power generating cells. This gives propulsion, as well as power.

Powerships and Floating Windfarms

Powerships are not intended as a permanent solution, but rather to handle peak demands, or fill in the gap while shore based systems are built or repaired.

There are 60 or more floating power stations operating in various locations on the planet. Most are privately owned, and leased out for profit. They are designed to operate continuously at full load. Originally built in older freighters, they are now using hulls specifically designed for their mission. Using an existing hull, a power ship can be outfitted in about 8 months.

It may surprise you, particularly if you live in Brooklyn, N.Y., that a 640 megawatt generating station is sitting on 4 power barges in Gowanus Bay. There are two additional barges at Sunset Bay. It is one of the largest such facility's in the world. The four barges are each fitted with 8 turbines. They tie into a ConEd substation with a 138 KV line. The facility was one of the first to be back in

operation after hurricane Sandy devastated New York City. The turbines can use natural gas or low-sulfur diesel. They keep about 1.5 million Brooklyn-ites happy and using their appliances. If the units are shut down, they can be providing power within 10 minutes.

A Ship can also be outfitted with wind turbines and towed to a favorable location. Fixed wind turbines are in use off the coast of many country's. The technology is mature. Wind Farm vessels are emerging as yet another solution to growing energy needs.

Cruise Ships

Plan to take a cruise? You might need to take along a power adapter to keep you cell phone or laptop charged. There are three primary power systems used in Cruise Ships, the US , the British, and the European. Ask the cruise Company which system they use and get the proper adapter. Usually, the cabins have a 110v outlet (standard, US) and a 220v (European).

Aircraft

Aircraft electrical equipment generally uses 28 volt power. The newer passenger airlines have 12 volt USB charging stations at the seats.

Military

The U. S. Military uses 28 volt systems for their ground systems. Submarines use rechargable batterys, or a nuclear power system for silent running. In the World War Two era, subs would have to surface to recharge the batterys with diesel-driven generators. The German Navy developed the snorkle, a tube that allowed the sub to remain submerged, and use outside air from above the surface.

Afterword

WE are dependent on our electrical generation and the Grid, or

distribution. Now, alternates to hydro power and steam powered generators give us more options, but don't always integrate into the existing system.

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Glossary of terms

3-phase -
AC – alternation current.
Active power - "real power" measured in watts.
AEP – Annual energy production
Aeroderivative – derived from aircraft technology.
Ampere – a unit of electrical current flow.
Apparent Power – product of the rms value of voltage and current. Units of volt-amps.
Arc – electrical discharge through an ionized gas.
ASIN – Amazon Standard Inventory Number.
BCDU – (ISS) Battery Charge-discharge Unit.
BESS – Battery Energy Storage Systems.
BEV – battery electric vehicle.
Black start – ability of a facility to start without external power.
BOEM – (U. S.) Bureau of Ocean Energy Management.
B&W – Burmeister & Wain Shipbuilders
ConEd – Consolidated Edison Co. New York.
Current – flow of electrical energy.
Cycle lifeloss of capacity in a battery, based on the number of charge-discharge cycles.
DC – direct current.
DOE – (U.S.) Department of Energy.
Dual fuel engine –can use liquid or gas fuels
Dynamo – a machine to convert mechanical energy into electrical energy.
EPC – Engineering, Procurement, and Construction.
EPS – electrical power system.
ERCOT = Electric Reliability Council of Texas.
ESS – (Tesla) Energy Storage System.
Floater – floating offshore wind turbine.
FPP- floating power plant.
FPSO – Production Storage and Offloading Units.
Generator – device to generate direct current.
IEC - International Electrotechnical Commission.

IGCC – Integrated Gasification Combined Cycle
IPP – Independent Power Producer.
Kilowatt - 1,000 watts.
Gas turbine – example is a jet engine for aircraft
Giga watt 10^9 watts
Giga watt hour – measurement of energy.
HPO – hydrogenated palm oil
HRSG – Heat Recovery Steam Generator.
IEC - International Electrotechnical Commission.
Inverter- device to convert direct current to alternating current.
LNG – liquefied natural gas.
LS – low sulfur.
Load shedding – the process of cutting off some loads so that others can be addressed.
Megawatt – 1,000,000 watts.
MG – marine grade.
NiCad – Nickle Cadmium battery.
NiMH – Nickel-Metal Hydride battery.
NOAA – (U. S.) National Oceanographic and Atmospheric Administration.
NPP – nuclear power plant
NREL – National Renewable Energy Laboratory (U.S.)
OCGT – open cycle gas turbine.
ORE – orbital replacement unit
Peaker – electrical plant to handle peak power demands.
Petcoke – a solid material derived from oil refining.
Power Barge – A power ship with no engines of its own. It is owed into position and anchored.
Power factor – ratio of actual electric power in an AC circuit to the product of the rms values of the voltage and current. Difference is due to the reactance in the circuit.
PPA – power purchase agreement
Reactance – opposition to the flow of current due to inductance of capacitance.
Reactive power – power which flows back and forth from the load,but does not do work. Units of var.
Rectifier – device to convert alternating current to direct current.

RMS – root mean square,
RTO – Regional Transmission organization
SAW – solar array wind.
SCADA - Supervisory control and data acquisition.
SOC – (battery) state of charge.
Spinning reserve – generation capacity that is online, but not connected.
Synthetic inertia – delivering power quickly when frequency deviates due to a disturbance.
TLP – tension leg platform
Transformer – a device to step up or down a voltage.
TSO – transmission system operator
VAR – volts-ampere reactive.
VAWT – vertical axis wind turbine
Volt – a unit of electrical potential
Watt- a unit of electrical power. Voltage times current.

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